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SPACECRAFT OPTICAL ENVIRONMENT

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This report summarizes the findings of the program entitled Spacecraft Optical Environment. In this program the Lockheed Palo Alto Research Laboratory conducted a research program to investigate the interactions of spacecrafts with low earth orbit environment. This program was specifically designed to provide information to answer the critical issues in understanding optical radiation produced by spacecraft when interacting with the atmosphere. The knowledge of the properties and the production mechanism of the many types of spacecraft induced radiation has application in spacecraft borne remote sensing, the detection and identification of spacecraft, and in the diagnostics of the physical and chemical interaction between spacecraft materials and their environment. The program studied radiation produced by spacecraft interaction phenomena related to (1) enhanced ionization in the vicinity of the spacecraft (2) chemical reactions of fast ambient species with spacecraft surfaces and (3) chemical reaction of fast ambient species with effluents and other gaseous products of outgassing and thruster firings. In addition the optical background radiation on which the spacecraft environment is superimposed was studied.

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TABLE OF CONTENTS

Page Numbers

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1.0. INTRODUCTION

This is a final report on the accomplishment of the Spacecraft Optical Environment program aimed at understanding spacecraft interaction induced radiation which is the primary diagnostic (1) of phenomena leading to enhanced ionization in the vicinity of spacecraft, (2) of chemical reaction of fast ambient species with spacecraft surfaces and (3) of chemical reactions of fast ambient species with effluents and other gaseous products of outgassing and thruster firings. The knowledge of the properties and the production mechanism of the many types of spacecraft induced radiation has application to understanding contaminants in spacecraft borne remote sensors and the detection and identification of spacecrafts and their optical signatures through the analysis of physical and chemical interactions between spacecraft materials and the environment. The Lockheed research laboratory has been in the forefront of spacecraft induced optical emissions ever since the discovery of the shuttle glow over a decade ago. Since then, many investigations studied spacecraft induced emissions including this program which is a collaborative program in which Lockheed has worked with the Air Force Phillips Laboratory and made a number of contributions. This report summarizes the present state of knowledge about spacecraft induced radiation and highlights the questions which still need to be addressed.

2.0. Spacecraft Optical Emissions

Glows associated with space experiments have been observed for some time. A rocket experiment flown into the mesosphere and lower thermosphere in 1956 [Heppner and Meredith, 1958] cited optical backgrounds in visible photometers near the 100 km altitude region. These early experiments noted background ratios in the background signal of photometer channels suggesting a continuum type emission. Nitrogen Dioxide emission was reported as a likely explanation of the phenomena. It wasn't clear in this early rocket data whether gas phase reactions were taking place with out-gassing contaminants or whether there was a surface reaction involved.

The AE-C and -E satellites were equipped with a Visual Airglow Experiment {VAE} which observed atomic and molecular features in the earth's airglow layer. Backgrounds in the filter photometer channels of AE-C were found to have a variability with ram angle below 170 km according to Torr et al., [1977]. A thorough analysis of the data from AE-C and -E was reported by Yee and Abreu [1982, 1983] over the altitude range of 140 to 300 km. The data displayed a detectable level of luminosity in the near UV channels of the instrument (3371 Å), with increasing luminosity towards the red wavelengths (7320 Å). The background in all filter channels, when plotted, described a bright ram source, increasing in brightness toward the red wavelengths. The analysis indicated that the glow extended well away from the spacecraft suggesting the probability that the emitter is a metastable. The Yee and Abreu [1982, 1983] analysis reported a strong correlation between the ram emission intensity and altitude. The emission intensity closely followed the atomic oxygen scale height above 160 km altitude. This discovery of the glow relationship to the oxygen flux was an important key to establishing and understanding of the physical process leading to the glow.

Glow observations have been reported by a number of investigators from Shuttle missions STS 3, 4, 5, 8, 9, 41D, 41G, 51D and 61C [Refs: Banks et al., 1983; Mende et al., 1983; Mende, 1983; Mende, 1984; Mende et al., 1984 a,b,c; Torr and Torr, 1984; Torr, 1985; Swenson et al., 1985; Mende and Swenson, 1985; Kendall et al., 1985 a,b; Mende et al., 1986; Swenson et al., 1986 a,b; Kendall et al., 1986; Tennyson et al., 1986] (See **Figure 1**). Banks et al. [1983] reported glow from orbiter television and still camera pictures around aft spacecraft surfaces while documenting glows associated with an electron accelerator experiment on STS 3. Ram glows associated with STS 5, 8, and 9, have been documented [Mende 1983, Mende et al. 1983, 1984a, 1984b] using an intensified camera. On the later missions (STS-8 and -9), objective grating imagery of spacecraft glow from the vertical stabilizer depicted a red structureless glow [Mende et al., 1984 b,c]. The spectral resolution was on the order of 150 Å. On the STS-8 mission it was observed that glows from surface samples including aluminum, kapton, and Z306 (a polyurethane black paint typically used in low light level detection instrument baffles) were not equally bright. The surface characteristic and/or the material make up clearly was shown to affect the glow brightness.

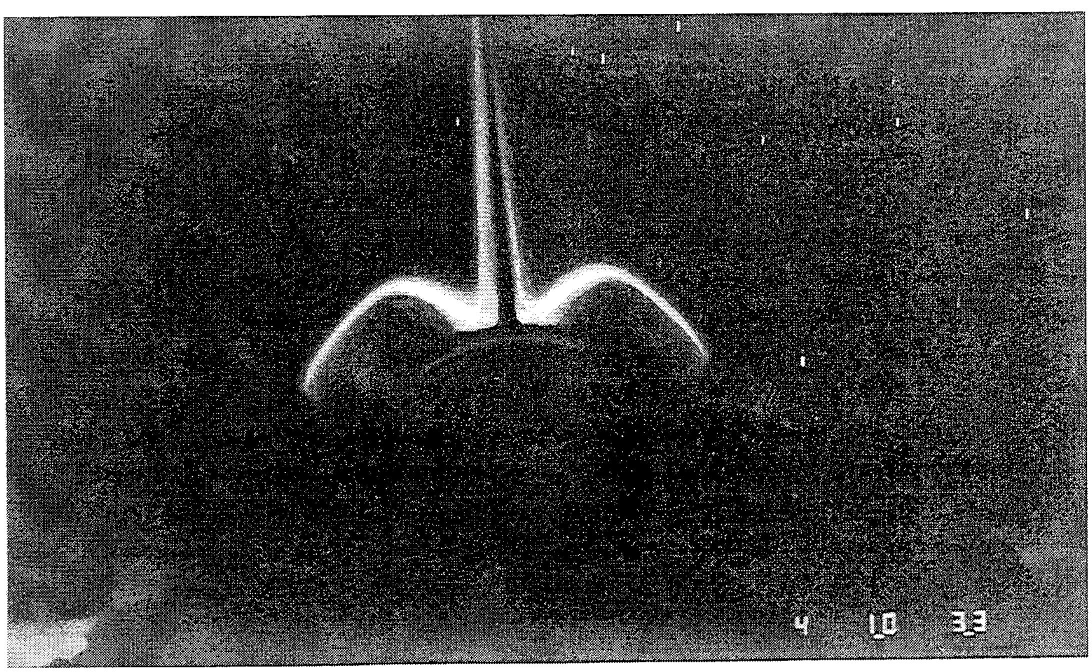

Figure 1. Orbiter Glow. Night view of vertical stabilizer and OMS pods from aft flight deck.

High spectral resolution measurements of the ISO spectrometer on STS-9 (Spacelab 1) show the presence of N_2 1PG bands [Torr and Torr, 1984 and Torr, 1985]. There are also a number of other observed emission features which may be part of the natural auroral and airglow background environment and, therefore, may not be part of the shuttle glow.

2.1. UV-FUV Glows

UV glows were reported in the 2800 and 3371 Å channels of the AE spacecraft [Yee and Abreu; 1982, 1983]. The UV glows were considerably weaker than those in the visible on that spacecraft. It has been postulated that the UV glows from NO might be likely on ram surfaces [Barrett and Kofsky, 1985; Green et al., 1985 a,b; Kofsky and Barrett, 1985; Swenson et al., 1985 and 1986 b]. Tennyson et al. [1986] reported no component of UV ram glow in their attempts on STS-61C. The 61C instrument was not looking at a surface and was a spectrometer with a small aperture. If UV glows are present from NO, they would be expected to be a very thin layer close to the surface. The Berkeley FAUST EUV experiments on STS-9 had fogged film and one of the contributing possibilities has been ram glow [Bixler et al. 1984]. S3-4 satellite UV instrumentation [Huffman, 1980] has found N_2 LBH emission to originate near the spacecraft [Conway et al., 1987]. Torr et al. [1985 b] have observed shuttle induced emission in N_2 LBH also. Kofsky [1988] and Swenson and Meyerott [1988] have proposed recombination of N on the surface as being responsible. Swenson and Meyerott [1988] have found that a large source of N is likely in the plow cloud of low altitude spacecraft due to atom exchange with the ramming atmosphere. **Figure 2** is a schematic description of the atom exchange process resulting in N surface doping and subsequent recombination, surface escape, and emission. The atom exchange mechanism predicts a source flux and altitude distribution that supports the observations. Meyerott and Swenson [1990] have described a set of possible surface interactions likely with fast N recombination including the possibility of 958 Å and 2800-3400 Å (Gaydon-Herman bands) from excited N_2. Swenson et al. [1995] have found that this process does not work effectively for non vibrationally excited N_2 such as found in the atmosphere. Meyerott and Swenson [1991] presented a chemical explanation for fast recombination of atomic N which would result in an N_2 upper state which would cascade to produce a source of N_2 LBH bands.

Chakrabarti and Sassen [1985] have reported anomalies in the FUV from data acquired on STP78-1 satellite. Interpretation of Lyman alpha (1215 Å) intensity modulation with ram angle suggest several hundred Rayleighs of unexplained emission. Conclusive deduction of the source was not clear in the report. A ram modulation of 400 Rayleighs in the LBH bands was also reported. These observations were made at 600 km altitude.

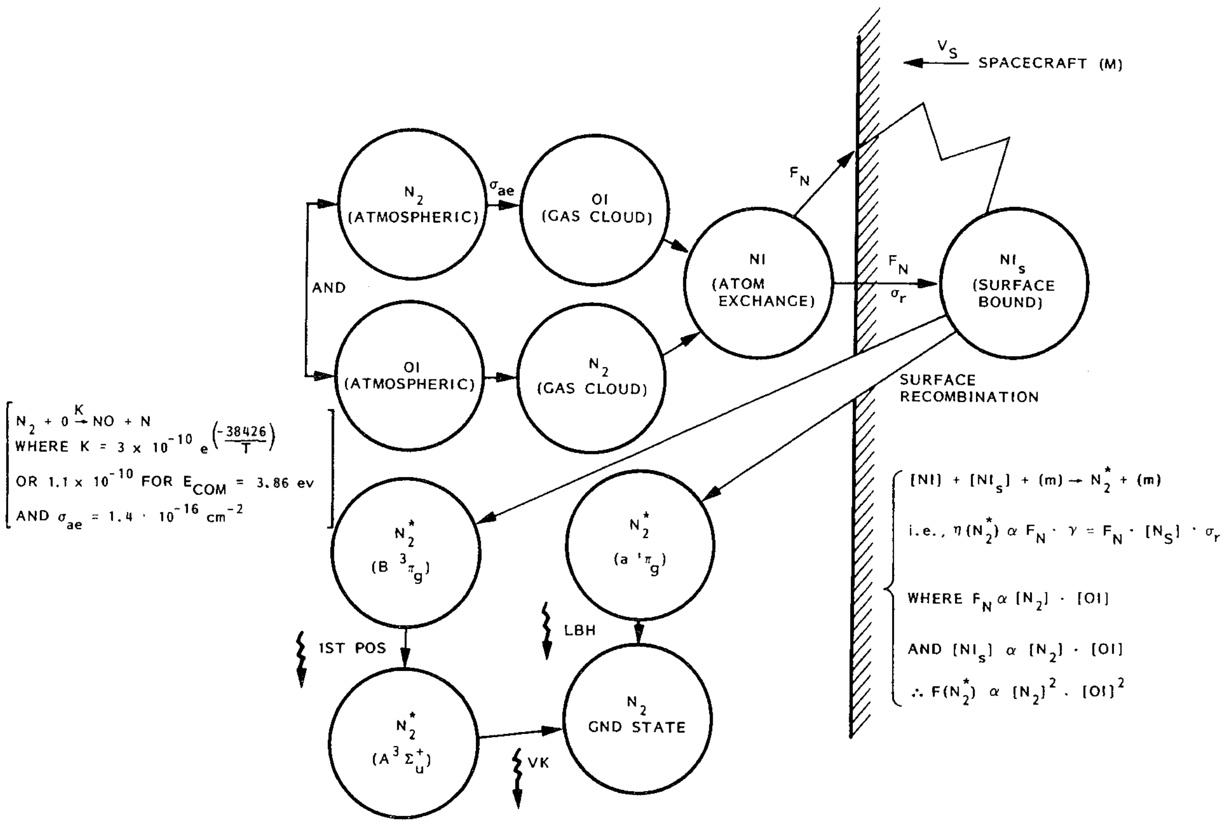

Figure 2. Schematic of atom exchange process.

2.2. Infrared Glows

Ground based measurements of the infrared shuttle glow have been reported by Witteborn [1984]. Also, the Spacelab 2 IRT experiment reported backgrounds which were much in excess of what was expected from natural causes. How much, if any, of the IR glow is related to the process producing the visible glow is not clear. The IR glows are extended well away from the spacecraft and are speculated to result from gas phase reactions of off gassing constituents including charge exchange with the ambient ionosphere.

Strides have been made in interpreting earlier IR data and acquiring new information. Meyerott et al. [1991, 1994] have further analyzed the Spacelab 2 IRT data and have produced detailed spectra of H_2O including vibration and rotational contributions from modeled, collisionally excited water vapor. Excitation cross sections were extrapolated from the measurement. In addition, an unexplained bright daytime glow near 3 microns was speculated to originate from excited H_2O^+ ions which would arise from charge exchange with ionospheric O^+.

New exciting data are coming from the results of the DOD STS-39 experiments including the SKIRT [Ahmadjian et al., 1992] and CIRRIS 1A [Dean et al., 1994 and Zhou et al., 1994]. Ahmadjian et al. [1992] have identified emissions from NO and NO^+. NO emissions are expected as NO is a surface precursor to the visible red glows. NO^+ was not expected and likely comes from NO charge exchanging with the ionosphere as the charge exchange cross section is very large. These NO glows were postulated to be near-field and were produced on a local sample plate. The glows were strongly ram moduled as if the glows were local to the sample. Dean et al. [1994] confirmed a measurement of H_2O rotational emission in the Shuttle atmosphere similar to that modeled by Meyerott et al. [1994]. The H_2O vibrational bands were also measured with intensities presented. Zhou et al. [1994] report detailed distribution of the H_2O bands have produced extended emissions in measurements in the 8-10 micron region.

2.3. Visible Glows

In regards to the visible shuttle glow, a spectrum was reported from STS 41D with 34 Å resolution by Mende et al., [1984b] and Swenson et al., [1985]. These data show the shuttle ram glow to be an emission continuum within the instrument resolution. This spectrum was convincing evidence to suggest that OH and N_2 1PG are not the emission species on STS.

The current evidence strongly suggests the visible glow associated with the ramming atmosphere is a result of NO_2 in recombination [Swenson et al., 1985]. The natural atmosphere is reacting with the 8 km/sec vehicle to produce the phenomena. According to this picture NO is produced by the spacecraft sweeping out atmospheric N and O. Some of the NO which forms, remains adsorbed by the surface. Wall catalytic formation of NO is well known to be efficient in laboratory experiments [Reeves et al., 1960]. NO reacts very quickly in 3-body recombination with OI to form NO_2. The surface monolayer of NO, then, is exposed to atmospheric OI on ram spacecraft surfaces. Since NO_2 is formed by ramming OI, the 5 eV OI also contains enough energy to unbond the formed NO_2 from the surface NO_2 having a complex quasi-continuous spectrum, the lack of distinct spectral lines in the glow spectrum is explained. **Figure 3** is a schematic describing the postulated sequence of chemical events occurring, leading to the emission process. The bottom portion of the diagram shows the ramming OI interacting with surface-sticking NO to form excited NO_2. The excited NO_2 which exits the surface, gives the red glow.

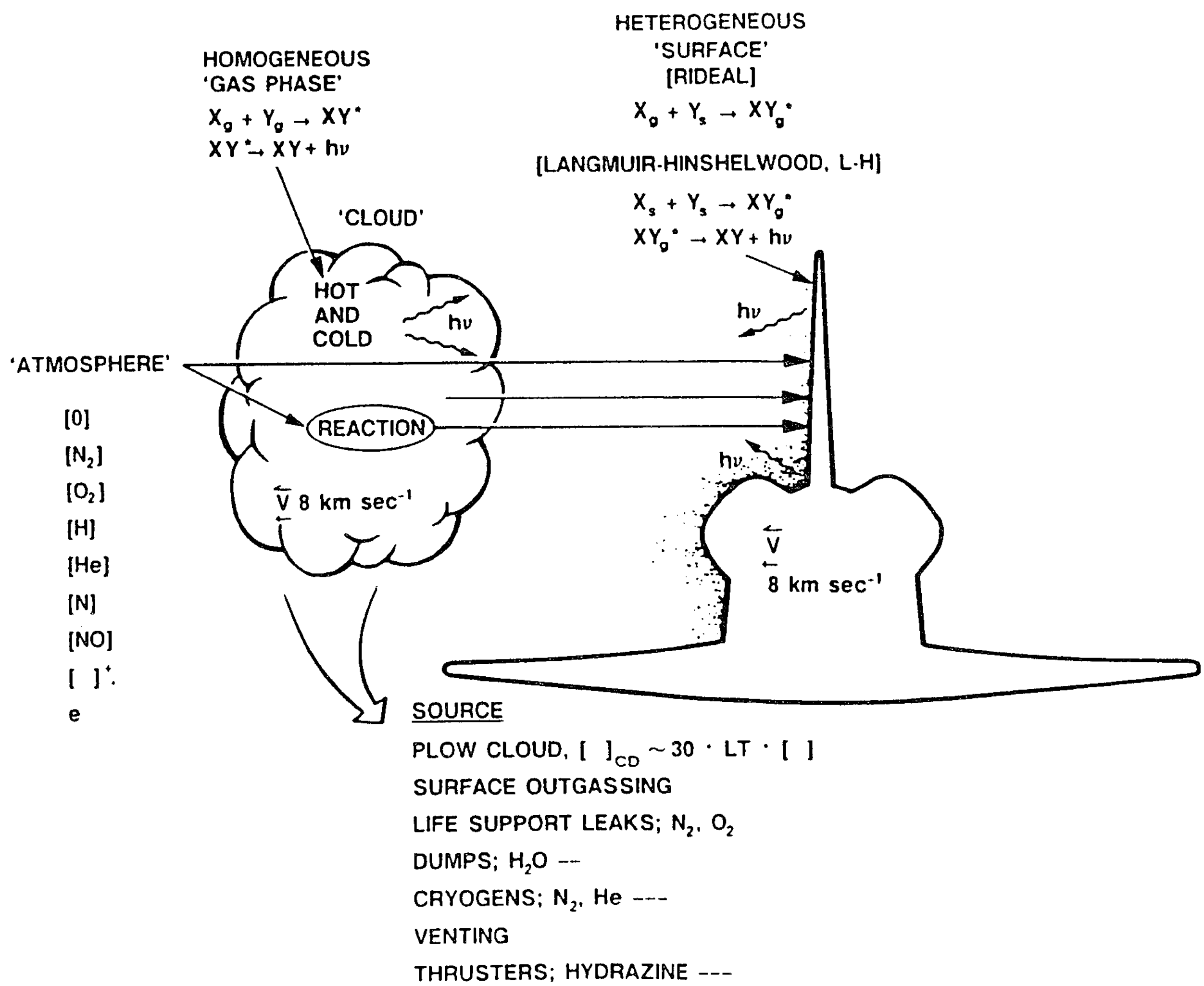

Figure 3. Chemical processes with the environment surrounding a large space vehicle such as the space shuttle orbiter.

The glow spectrum from 3-body gas phase recombination of laboratory experiments [Paulsen et al., 1970] is blue shifted from the shuttle observations but very similar in shape. The most critical aspect of the NO_2 theory is the lifetime considerations. Yee and Dalgarno [1983] analyzed shuttle data to deduce an average molecular travel of 20 cm [confirmed by Swenson et al., 1986a]. The 70 ms lifetime determined by Schwartz and Johnston [1969] or 40 ms of Bylicki et al. [1984] suggest the NO_2 must be exiting the surface with 2-4 eV transitional energy to account for the observed thickness of the glow. There is sufficient energy in the ramming OI to account for the rebound energy. It is, however, unprecedented in laboratory experiments to have such an "elastic" process in the surface recombination.

The best evidence for NO formation and sticking on orbiting surfaces is reported by the mass spectrometer investigations and what has been observed in the way of NI, NO, and NO_2. Engebretson and Mauersberger [1979] described in detail, the response of NO with respect to thermal and orbital parameters for their instrument on AE-C satellite. It has been known since mass spectrometers first flew, that most of the atmospheric NI entering the mass spectrometer orifice, converts to NO with wall collisions and in fact, a large percentage of the NI signal is deduced from the NO [mass 30] signal in the instruments (see Engebretson and Mauersberger, 1979 and the references cited therein). It has been well established in laboratory experiments that the NI and OI wall reaction form gas phase NO. Engebretson and Mauersberger [1979] then reported a most interesting phenomenon. They reported that NO was absorbed on the spectrometer walls (with efficiencies higher at low wall temperatures). The top part of the chemistry shown in **Figure 2** reflects what has been observed in the mass spectrometer orifice. They observed the gas phase NO, and from temperature and altitude geometry, they deduced that a significant amount of NO was sticking to the wall. More recently, Engebretson [1986] and Engebretson and Hedin [1986] have presented detailed analysis of specific orbits of DE satellite wherein the wall effect in the mass spectrometer orifice is pronounced with wall temperature modulation. Von Zahn and Murad [1986] have found from mass spectrometer measurements from a shuttle mission (STS-41B) that the exit flux of NO_2 is more than sufficient to account for the observed glow intensities reported on earlier missions.

The analysis of intensity of shuttle glow has been performed on several missions. The measurements from STS-41G at low altitude added a confusing data point to the existing data base. The intensity on this mission was much less than it had been measured on previous missions [Kendall et al., 1986]. After further investigation, it was found that the surface temperature for this particular observation was much warmer than earlier observations. A study of all the previous intensity measurements along with a thermal modeling study of the tile temperature for the associated glow measurements was undertaken. When the temperature history of the ram tile surface was modeled for three measurements of glow intensity from three different missions, it was found that the results of this study [Swenson et al., 1986b] were consistent with the NO theory and in fact provided a measure of the surface bond energy the NO had with the surface (~0.14 eV). The study further suggested that the lesser intense glow seen on the AE spacecraft (which had surface temperatures much warmer than the shuttle tile during observations) was also consistent with these findings.

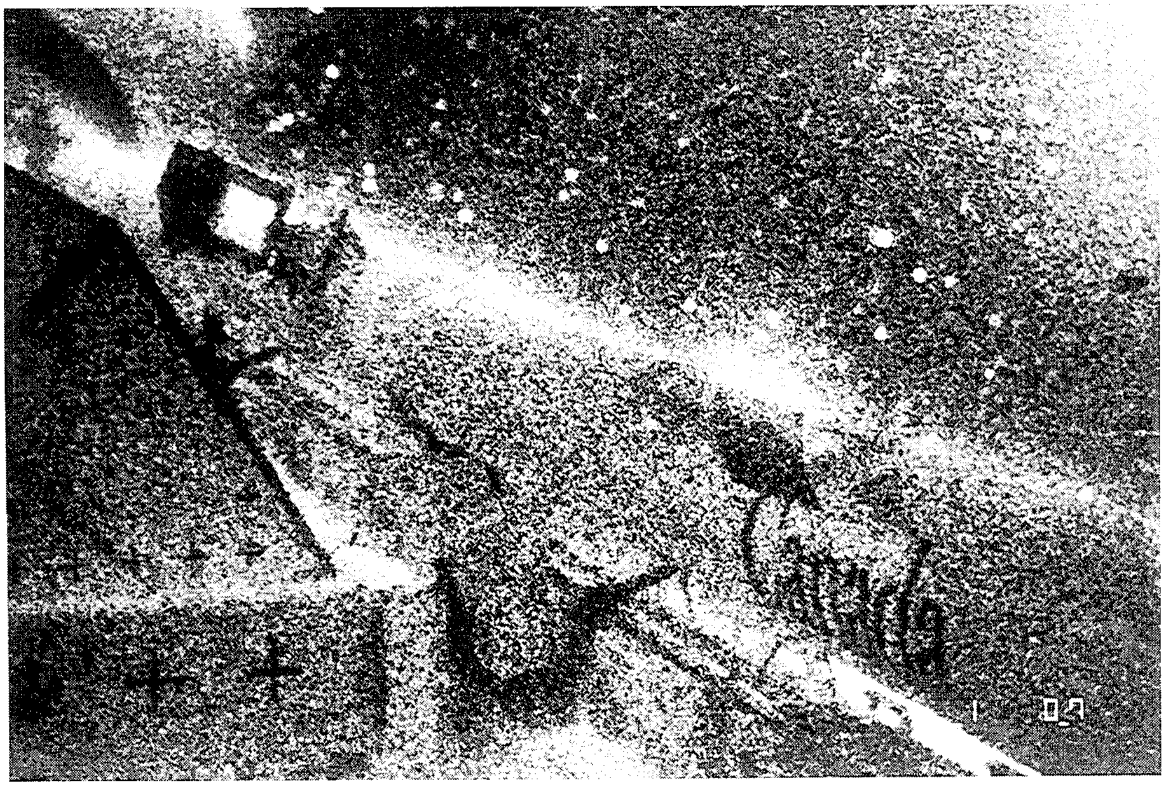

Figure 4. The arm and the different glows on the arm.

In **Figure 4** we present a picture where the apparent glow intensity above surface samples varied in intensity over respective samples. A thermal model was constructed for these material samples which were mounted on the insulating beta cloth on the RMS. The predicted glow intensity associated with the modeled temperature of each material sample was found to be in good qualitative agreement with the measured intensity associated with each sample. The emissivity associated with each material was largely responsible for the different cooling rate associated with each sample. The early conjectures, that material traits such as cleanliness or a surface chemistry associated with one and not the other, we feel were incorrect and that temperature can largely explain what we saw.

In the near infrared we would expect to see some emission intensities due to the near IR portion of the NO_2 continuum. It was shown in laboratory experiments that the shape of the NO_2 continuum strongly depends upon the type of reaction which produces the NO_2. Since the shuttle glow production is some form of surface catalytic reaction it is not surprising that the shuttle glow continuum is somewhat red shifted from the spectrum of the laboratory produced gas phase reaction [Swenson et al., 1985].

Laboratory experiments have now been performed which have simulated the shuttle glow [Caledonia et al., 1990, and Swenson et al., 1991]. In these experiments, material samples including Z306 Chemglaze, Al, and Ni were doped with NO which was exposed to an 8 km s^{-1} (5 eV) O beam. Heterogeneous recombination of NO and O to form NO_2^* resulted in emission spectra which were nearly identical to that of shuttle glow measurements [Viereck et al., 1992]. In addition, the lifetime was measured to be 185 msec which was consistent with the shuttle glow e-folding distance for a thermalized emission. This is in reasonable agreement with Greer et al., [1993]. The earlier assumption, that the NO_2^* lifetime was 70 μsec, leads to speculation that ram energy was carried into the exiting NO_2^* in order to account for the e-folding distance, was incorrect. The material was cooled from 300 to 77 K and brightening by an order of magnitude was observed, similar to shuttle glow [Swenson et al., 1986b]. The cooler surface is more effective at accumulating NO (or O) for a given fluency of the precursor species resulting in brighter glows. Spectrally, the NO_2^*continuum peak was measured at 7000Å for Chemglaze, and 7500Å for Ni compared to space shuttle measurements of 6800Å for shuttle tile. It appears that the laboratory experiments are supporting the theory that shuttle glow is surface catalyzed NO_2^*, likely produced by L-H recombination of NO and O. Swenson et al. [1991] contend the spectral shift from material to material is due to the difference in bond energy the surface bound constituents have to the surface, which shows up as vibrational relaxation in emission. Viereck et al. [1992], found that shuttle glow measurements, when properly corrected for window transmission, yield a spectrum much closer to the laboratory spectrum.

Regarding the AE glows, Yee and Abreu [1990] have re-examined the data assuming a continuum rather than line emission in their earlier studies. They find the spectra of the AE data are very similar to shuttle glow spectra. Subtle differences may be explained by the material influences on the spectral shape found by Swenson et al. [1991]. Dynamic Explorer data is not explained by this scenario, however. Copeland and Slanger [1990] have further spectral support that the DE spectra at 7320Å can be synthesized with OH emissions when including new laboratory measurements of v=11 emission lines. This is very puzzling and is not consistent with other spacecraft spectral measurements made to date.

Heterogeneous recombination of O with surface-bound NO has been confirmed to produce the shuttle glow in recent experiments. First, Swenson et al. [1991] reproduced the shuttle glow in the laboratory with a 5 eV (orbital velocity) O beam with surface doped NO. The shuttle glow spectrum was reproduced as was the effect of increased glow intensity with cooler surface temperatures. In addition, Viereck et al. [1991] published the results of a NO release on a space shuttle flight which doped shuttle surfaces, and bright shuttle glows were produced. The theory for how NO_2 is produced is no longer a mystery. The mystery remains, where does the NO come from? Some of it is produced from the atomic N scavanged from the upper atmosphere through surface reaction with O. Some NO is absorbed directly from the atmosphere. Is NO produced in the vehicle clouds through atom exchange?

2.4. Thruster and Thruster Effluent Induced Glow

It is by now well documented that when the vernier thrusters on the shuttle are fired, there is a large enhancement of the surface glow, in addition to the bright gas phase glow region that is apparently not associated with surface processes. The latter is quite transient and must be very bright, whereas the surface glow persists for times on the order of 30 s before fading to the normal background glow level. The investigation of this gas phase glow has gained importance lately because this provides an opportunity to study the interaction of unburned rocket fuel with the ambient atomic oxygen atmosphere.

The thruster fuel is monomethylhydrazine which combines with nitrogen tetroxide, and the principal neutral products in the atomic O environment, according to Murphy et al. [1983], are H_2O, N_2, CO_2, CO, and H_2 (or monomethylhydrazine). The neutral densities are typically 7-8 orders of magnitude higher than the charged particle densities. It has also been claimed that there may be substantial amounts of unburned fuel at the beginning and end of a thruster firing.

It was cited by Mende et al. [1988a,b and earlier references] that the vernier thruster effluent influences the ram glow at times. It appears that when the effluent cloud travels in front of surfaces in ram, enhanced ram glow intensity occurs. Recently, this has been interpreted by Swenson and Meyerott [1988] to be a result of the atmospheric O ramming into the gas cloud (which contains a significant amount of N_2). The atom exchange between O and N_2 results in a large flux of N and NO emanating from the lee side the cloud, which impinges on the surface. The additional layer of NO on the surface provides a new source of NO for ramming O to interact with to produce NO_2, according to their theory. This should also result in enhanced N_2 LBH bands, if this is what is occurring. Hunton [1994] and Hunton and Machuzak [1994] have verified the production of N and

NO products in O bombarded thruster plumes. The subsequent doping of surfaces by these heterogeneously reactive constituents which are then bombarded by ram O confirm the enhancement of glow as proposed by Swenson and Meyerott [1988].

Pike et al. [1990] and Murad et al. [1990] have performed H_2O release experiments in the ionosphere from space shuttle. Cloud dynamics and optical yields resulting from cloud-ionosphere interaction are discussed as well as model references.

Shuttle exhaust plumes can interact with the atmosphere in various ways to produce emissions. Broadfoot et al. [1992] measured some of the optical properties of the shuttle plumes by ground based telescopes. They discussed the observation of the thruster induced 630 nm emission from an exhaust plume due to $O(^1D)$. They propose two mechanisms for generating the $O(^1D)$ state:

$$O^+ + H_2O \longrightarrow H_2O + O(^1D) \quad (1)$$

$$O(^3P) + X \longrightarrow O(^1D) + X \quad (2)$$

where X is any exhaust species with sufficient kinetic energy to excite the $O(^1D)$ line. The cross sections are not known for either reaction. Recently, Viereck et al. [1993] found that under certain circumstances thruster firing will produce the $O(^1S)$ state because they observed 557.7 nm emission in the plume. It appears that the plume ejections need to be directed into the ram to produce the kinetic energy (>4 eV) in the c. g. frame of reference to permit the production of the $O(^1S)$ state. In addition to these line emissions, plumes show an intense spectral continuum created probably by NO_2 glow.

Viereck et al. [1994a] describes the details of shuttle plume emissions as measured from an aft flight deck spectrometer on space shuttle. Viereck et al. [1994b] have found enhancements of OI 5577 and 6300 Å emissions in thruster effluent plumes and provide theories for formation.

The reader is referred to Mende et al. [1987], Garrett et al. [1988], and Slanger [1989] for review articles on the spacecraft glow phenomena. There are still several open questions about the mechanisms which play a part in thruster induced luminosities in the visible, IR and UV wavelength bands.

2.5. IR Glows

Ground based measurements of the infrared shuttle glow have been reported by Witteborn [1985]. Also, the Spacelab 2 IRT [Koch et al., 1987] experiment reported backgrounds which were much in excess of what was expected from natural causes. The IR glows are extended well away from the spacecraft and are speculated to result from gas phase reactions of off gassing constituents including charge exchange with the ambient ionosphere.

Shimazaki and Mizushima [1985] predict a mechanism for shuttle glow production in which the NO molecules get vibrationally excited through collision with shuttle surfaces. Green et al. [1985 a & b] make a case for NO vibrational overtone transitions having a substantial contribution in the visible region. If this were correct, then the corresponding IR transitions at 2 and 3 microns would be several orders of magnitude greater than the visible component. They suggest that the glow intensity might be comparable to earthshine in the infrared and therefore may be several mega-Rayleighs of emission.

Torr [1988] has reported that at lower altitudes (250 km and below) a spacecraft will generate a dense layer of gas due to the "snow plow" effect. Accordingly in the spacecraft frame of reference, the fast streaming ambient atmospheric molecules have a large probability of collision with the particles which are caught in this region. Because the masses are generally similar there will be a very efficient re-distribution of the ram energy of the incoming molecules. This would result in a high kinetic temperature in this dense region. Although no mechanism was proposed for transferring the kinetic temperature into the molecules electronic state, it was suggested by Torr [1988] that this region would produce intense gas phase molecular emissions in the IR region.

Young and Herm [1988] have modeled the observations of CIRRIS 1A IR instrument flown on Space Shuttle. Water vapor was the prime consideration for contamination of that instrument as it was for the Spacelab 2 IRT experiment.

Koch et al. [1987] described the analysis of contamination to IRT on space shuttle as mostly due to collisionally excited H_2O. Data in the 1.7-3 micron channel on that instrument was speculated to be mostly OH. Meyerott et al. [1991] performed an extensive study of the IRT data. They deduced a column density of H_2O from resonance in the 1.7-3 micron channel. They found that the emissions measured in 3 channels between 4 and 14 microns were consistent with collisional excitation of O with H_2O and inferred cross sections which could be compared with theories of Johnson [1986] and Redmon et al. [1986]. Their findings suggest that the 'nighttime' intensity of the 1.7-3 micron channels is also consistent with H_2O but daytime intensities are much larger than can be explained by H_2O collisional excitation. The modeling considerations assumed a 2 eV rotational distribution for the H_2O stretching and bending modes. H_2O (0,0) vibrational was also found a strong contributor above 7 microns. **Figure 5** [Meyerott et al., 1991] is a model of the band head positions between 1 and 8 microns for H_2O as well as for H_2O^+. Charge exchange of ionospheric O^+ is postulated as a likely source of daytime emission in the 1.7-3 (S-Band) channel of the IRT experiment. This aspect is still under investigation.

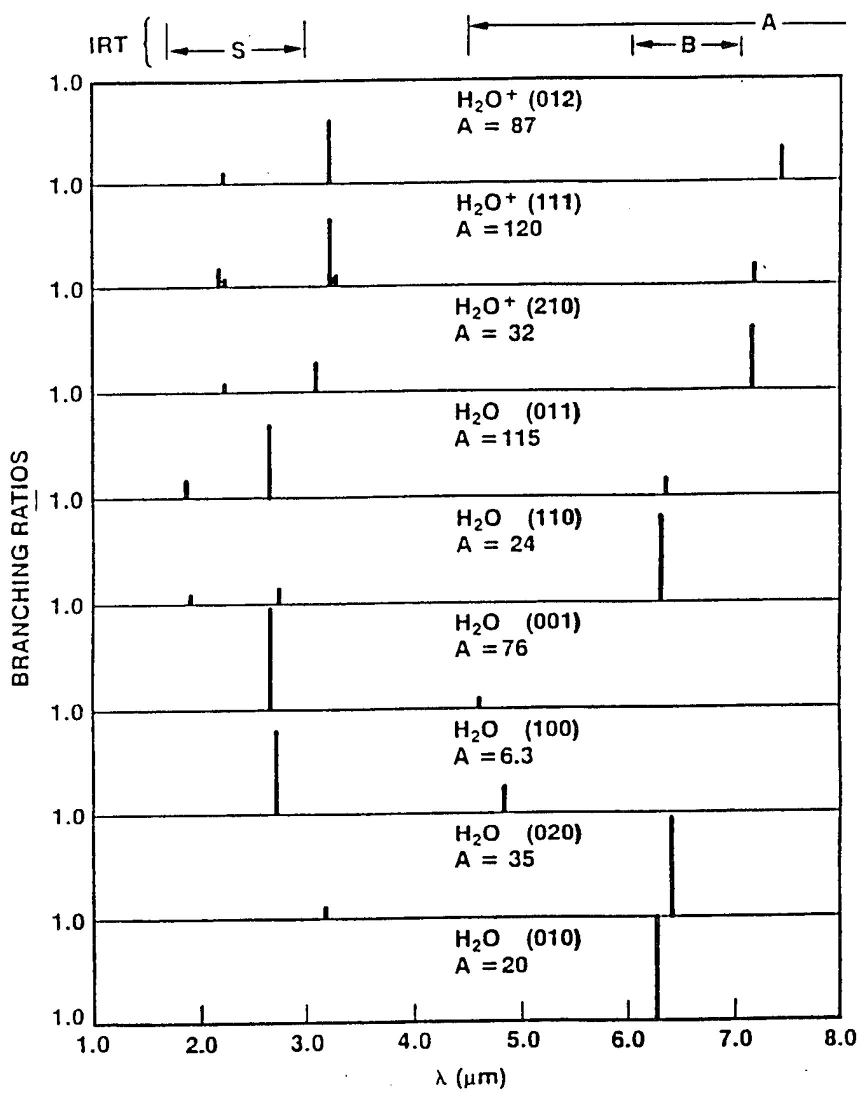

Figure 5. The models of the water bands.

During the STS-39 mission, a cryogenic infrared circular variable filter made measurements in the 0.7 to 5.4 μ range [Ahmadjian et al., 1992] in the shuttle payload bay. Their data is reproduced in **Figure 6**. The top panel shows the quiescent shuttle glow which was obtained by long time signal averaging. The instrument sensitivity presented in the paper would not permit the measurement of the quiescent shuttle glow to these levels without substantial time averaging. The middle panel shows thruster glow in the infrared. During firing, the signal intensities vary in size to 10^{-8} to 10^{-7} w/cm^2 sr μm. The thruster spectrum appears to contain NO, NO^+, OH and CO. The third panel shows earth limb for intensity comparison and it shows that there can be a strong background component due to the earth limb.

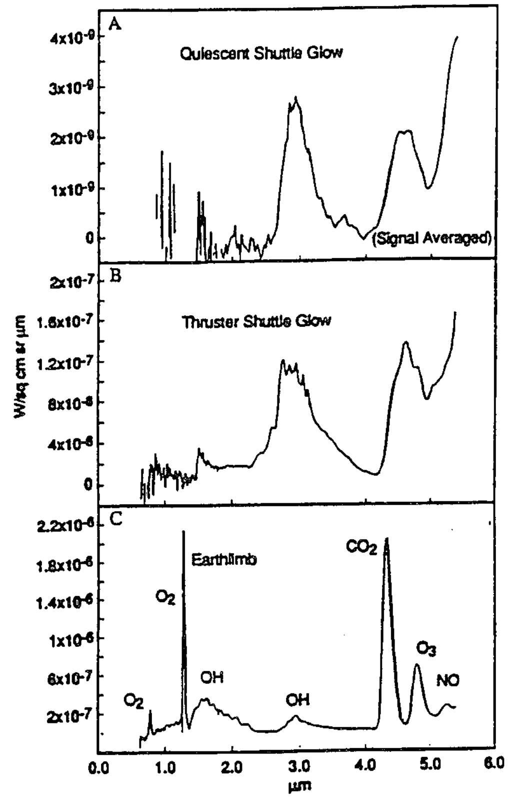

Figure 6. (a). Signal averaged spectrum of quiescent shuttle glow; (b). Spectrum of shuttle glow during a thruster firing; (c). Earth limb spectrum. Shuttle attitude is nose down gravity gradient with bay toward wake [Ahmadijan et al., 1992].

In summary, there is still considerable uncertainty about the shape and distribution of the IR emitting gas clouds around the spacecraft. Infrared imaging spectroscopy is required to describe the spectral and spatial profile of these emitting regions and to permit characterization of the production mechanisms. New measurements from STS-62 one being published by Swenson et al., [1995].

There are several questions related to the production of near IR emissions in the vicinity of spacecraft from gaseous clouds created by the spacecrafts. The investigation of these emissions require the construction of an IR imaging spectrograph which takes data simultaneously in a wavelength region from 1 to 3.2 μ and which produces a line image or spatial profile in a direction perpendicular to the wavelength resolving direction. With the development of high resolution near IR focal plane arrays, such a spectrometer can be built with very high sensitivity when compared to more conventional IR photometers previously used in shuttle borne observations.

There is evidence that glows occur in the UV and FUV regions. For the investigation of these emissions, a UV sensitive flight camera should be flown.

Spacecraft glows are a manifestation of colliding and chemically reacting atoms and molecules in the spacecraft environment. Primarily the glows result from spacecraft-atmosphere interaction. Orbiting vehicles with velocities of ~8 km s^{-1} and rockets with velocities of ~1 km s^{-1} collide with atmospheric constituents (neutral and charged) to interact on surfaces and surrounding gas clouds.

Figure 1 is a summary schematic of shuttle ram glow and related effects which describes the general chemical processes involved. One the left of the Figure are listed the atmospheric constituents available in low earth orbit (LEO), where relative constituent populations are ordered top to bottom for a 250 km altitude. A schematic cloud (which normally surrounds the vehicle) is shown in the middle and spacecraft on the right. The sources of the vehicle cloud products are summarized at the bottom. All vehicles have a plow cloud which results from a pile up of atmospheric constituents on the ram side of satellites as a result of constituents exiting surfaces much more slowly than the vehicle is plowing through them. Vehicles which have recently left the earth environment often are laden with H_2O and manufacturing contaminants which offgas in orbit until they are depleted from the surface. Manned vehicles have life support systems which can leak breathing air and which often dump waste water. Orbiters often carry cryogenic systems which offgas or vent. Attitude control systems eject material into this environment, all of which contribute to the vehicle environment "cloud". The ram atmosphere can interact with the cloud constituents and the cloud constituents can collide and chemistry can occur without external stimulus. These gas-gas reactions are considered homogeneous reactions. The source of atoms and molecules to the surface include the atmosphere directly, of course, but also the reaction products of the atmosphere-cloud chemistry. As atmospheric constituents interact with cloud constituents, the products retain the momentum which will cause ram side homogeneous chemical products to ram to the orbiter surface. In a sense, the homogeneous chemistry in the plow cloud are precursor reactions which may effect the surface chemistry. Reactions which occur as a result of the surface are called heterogeneous reactions. The gas-surface reactions are called Rideal processes, whether the gas source is the atmosphere, cloud, or homogeneous chemical product constituents. The surface-surface reactions are called Langmuir-Hinshelwood (L-H) processes.

In the discussions to follow, the wavelength regions are divided into visible glows which include the well known "red" shuttle glow, the far ultraviolet (FUV) where excited molecular nitrogen bands have been observed, and the infrared (IR) where the water molecule emissions have been detected.

In summary, the visible shuttle glow is now believed to be a result of NO_2^* emission where the NO_2^* is produced through a surface L-H process with NO and O. The source of the O is the atmosphere. There are several contributions to NO at the spacecraft of which the three most important are presented by Viereck et al. [1992]. The predominant role of NO_2 is that the shuttle glow was confirmed by Viereck et al. [1991] in a shuttle experiment in which NO gas was released which increased the brightness of the shuttle glow. A recent laboratory study and a comparison with spacecraft glow on the Atmospheric Explorer (AE) suggests that the NO_2 glow production is predominantly responsible for laboratory, spacecraft and shuttle luminescence [Greer et al. 1993]. The FUV glows producing N_2 emissions result from either a Rideal or L-H process where some N is available from the atmosphere but most is believed to come from the atom exchange which also produces the NO discussed above. In the IR, H_2O becomes collisionally excited from ramming atmospheric O, which in turn cascade to produce emission between 2.5 and 14 μ. Thruster glows are phenomena involving relatively large chemical releases into the atmosphere. Little published information is available on these phenomena, but better data should be forthcoming. Most reactions of importance are anticipated to be atmosphere-effluent reactions.

2.6. Summary of the EISG Experiment Results Relevant to the SOE Program

The following is an abbreviated report of some of the unpublished results relevant to the SOE program from the EISG experiments during the STS-62 mission.

The Experimental Investigation of Spacecraft Glow [EISG] was one of two experiments manifested aboard the Office of Aeronautics and Space Technology [OAST]-2 payload to study and characterize spacecraft glow. The EISG experiment consisted of a 1x1 meter sample plate, half of which was coated with a black paint typically used in instrument baffles and the other half with a white, insulating paint. The area above the sample was viewed by Visible [VIS] and Far ultraviolet [FUV] spectrometers, an FUV photometer and Infrared [IR] radiometers to characterize spacecraft glow under a large number of conditions. The experiment set out to study the glows at the wide range of wavelengths to characterize the atoms and molecules responsible for glows, glow intensities vs. sample material, sample temperature, ram attitude angle, and altitude. The EISG also contained a nitrogen [N_2] gas release to study chemistry with ram atmosphere which was expected to produce glow producing compounds. The sample plate contained temperature sensors. A mirror system allowed time sharing of spectrometer views over respective materials. The instrument operations were executed by a dedicated computer which received time line instructions via ground commands from the Payload Operations Command Center [POCC] located at NASA Goddard Space Flight Center. Data were downlinked through a low rate channel [1200 baud] and a Medium Rate Data [MRD] channel [0.5 Mhz]. Two dedicated tape recorders with data capabilities of 5 hours each, were used to buffer data when downlink was not available.

The Spacecraft Kinetic Infrared Test [SKIRT] experiment consisted of a cryogenically cooled infrared spectrometer dedicated to glow characterization in the 1-5 micron spectral region. The two experiments worked together to provide simultaneous observations of glow phenomenology.

Prime operations for EISG consisted of one orbital night operation [~30 minutes] with dedicated attitude maneuvers, data downlink, and on board camera operations. The onboard cameras included an image intensified film spectrometer/imager operated from the aft flight deck window by the mission specialists and an orbiter black and white, low light level, video camera. The prime operation data takes were preceded by a dedicated attitude which exposed the EISG sample to deep space for the purpose of cooling the sample. All prime operations ran as scheduled with exciting results. Data were collected at the 140 nautical mile altitude on our 4 scheduled prime operations and during 10 additional orbits. At the last mission phase, we accomplished 3 prime operations in elliptical orbit with 105 nautical mile perigee and acquired data on an additional 10 elliptical orbits. The last 3 night passes were taken after the TDRS antenna was stowed on the orbiter and MRD data were no longer available. Data, logging continued to the on board tape recorders before deactivating the experiment.

The original plan was to use a specific orbiter camera [camera D] located on the forward-starboard bulkhead to provide high time rate images of the visible glow emissions, but it failed early in the mission because of a failed shutter. The only other low light level camera was the RMS wrist camera. We used that camera for EISG prime operations. This support involved the deployment of the RMS and positioning the camera line-of-sight. The viewing perspective was optimized by locating the camera precisely in the plane of the sample plate. This view produced excellent results.

Gas Release Observations. During the N_2 gas release, the glow was extinguished during release times and reappeared after the release was complete without enhancement. It is well known the NO [nitric oxide] dopes surfaces that, when subsequently bombarded by ram O, makes NO_2^* and associated emission as the NO_2^* leaves the surface. This process has been validated in our own ground chamber experiments as well as on STS-39. It is known that some NO is present in our earth's atmosphere and early theories suggested the atmospheric source was the sole source of NO. It was proposed later that NO could be made chemically by $O + N_2 \Rightarrow NO + N$, where the O is ram from the atmosphere and the N_2 is resident in the spacecraft environment. The minimum energy required to make the reaction is 3.86 eV. The ram O has a translational energy of ~5 eV which is sufficient energy to make the reaction occur.

Thruster effluent has been observed to pass in front of surfaces and, in some cases, the effluent is collisionally thick so the glow is extinguished [temporarily] but then enhanced by several orders of magnitude. We have postulated that $O + N_2 \Rightarrow NO + N$ is responsible for those previous observations, see below for further discussion.

As we released N_2, we expected the ram glow to be somewhat diminished [but not extinguished] while the N_2 stopped the atmospheric O from reaching the sample. The N_2 acts as a collisionally thick barrier to stop the ram atmosphere before it collides with the surface. As the N_2 gas was turned off, the NO and N products on the ram side of the release cloud should dope the surfaces, provided they were produced. We saw no sign of this in any of the emissions. In the VIS, IR, and FUV, emissions were either partially or totally extinguished without any subsequent enhancement. The SKIRT experiment also verified the IR emissions were extinguished or significantly diminished. We performed releases which were long [60 s] and short [2 s]. No enhancements were noted in any of the releases. The OAST-2 Solar Array Module Plasma Interaction Experiment [SAMPIE] provided by NASA/Lewis measured invaluable pressure data near the glow instrumentation during gas releases and during elliptical orbits which will be very useful in the data analysis phase of this investigation.

On a separate note, one of the valuable insights [not considered beforehand] was the fact that the gas release extinguishes glows in the near vicinity [~few meters] but not far field. The molecules producing infrared [IR] emissions have varied lifetimes. Short lifetimes would emit near surfaces but others are long allowing emissions to emit 10's to 100's of meters from the spacecraft. The SKIRT experiment noted changes in intensity of some emissions more than others. The release then acted to sort near and far field emissions by quenching near field emitters.

Thruster effluent frequently doped the sample surface. During those doping, while in ram, enhancements were observed in the Visible, FUV, and IR. {A new publication by Hunton [J. Geophys. Res., 99, p.3999, March , 1994] using STS-4 data from a quadrapole mass spectrometer shows that NO is increased from thruster firings primarily on orbiter ram surfaces}. The effects, we observed optically, suggest that the NO and N products in the thruster gas are producing these optical enhancements. The thruster effluent cloud includes ~1/3 mole fraction of H_2O and N_2, significant amounts of CO and H_2, and minor amounts of CO_2, O_2, H and MMH-$N0_3$. NO, and N are not products of the vernier burn so these products are possibly made as a result of the effluent clouds interacting with the atmosphere. Our contention would be that NO and N are made through atom exchange between the thruster effluent N_2 and atmospheric O. One possible difference between thruster effluent N_2 and the gas release N_2 is the thruster effluent N_2 is vibrationally excited whereas the gas release N_2 is not.

One point of interest is that thruster effluents aimed at surfaces have been believed to be the main agent responsible for thruster doping other surfaces since the object surface scatters the effluent to other surfaces. It is also noted that effluent clouds become dragged into surfaces by atmospheric momentum. We also noted, however, that thruster effluent ejected into ram is slowed by the atmosphere and eventually overtaken by the orbiter.

Normal ram glow at the beginning of the mission (at 160 nautical miles altitude) was extremely weak. The atmospheric density was very low since the solar cycle was near sunspot minimum. It is likely that the data has to be integrated an entire orbit to resolve a good visible spectrum at the high altitude.

Due to the elliptical orbit of part of the mission there is a good data set to determine intensity as a function of altitude. From this data set it might be possible to resolve whether the visible glow intensity truly follows the O scale height as it does on the small satellites. In the FUV wavelengths, glows were observed but we did not notice enhancement in the N_2 Lyman Birge Hopfield [LBH] bands as predicted.

During the mission several roll maneuvers were made. Roll modulation of the glow was dramatic, as expected. Several atomic oxygen lines were present in the roll modulation data at low altitude. Data also exist to compare temperatures for a given sample for a temperature range from ~ –70 to +20° C and on the effective cooling and heating rates from the radiative environments. We will also resolve whether aerodynamic heating became a factor at the elliptical perigee altitudes.

In the above paragraphs, we have summarized what is generally known about glows and their sources. This summary presented here is to define the state of current understanding and to show how our work contributed to the current state of knowledge in the field.

3.0. SOE Program Activites

In this program the Lockheed Palo Alto Research Laboratories performed an experiment to observe aurora, airglow, shuttle induced emission effects in collaboration with the Air Force Phillips Laboratory. The primary thrust of the program was to obtain observations of the quiescent shuttle glow and thruster induced emissions. The experiment was code named as Auroral Photography Experiment (APE). The Lockheed tasks associated with this program were the provision of the experiment hardware and assistance of the Air Force in the flight operations requirements definition and participation in flight operations during actual flights. In addition, there was an active parallel data analysis effort of the data taken on APE experiment on prior missions.

As a brief summary, the APE experiments are shuttle cabin mounted experiments in which the orbiter crew takes optical observations through the windows. There are several components of the APE experiment which represent different hardware configurations. The APE configuration B consisted of an image intensifier with filters, filter changer, Spectrometer, 50 mm focal length spectrometer lens and a Fabry-Perot etalon interferometer. It was a planned that for the follow on APE missions the Lockheed IR photometer would have made measurements of the shuttle glow and thruster glow components in the near IR wavelength regions. This configuration known as APE-C was to augment the APE flight hardware by including an infra-red photometer detector head, electronics box and flight cables.

3.1. APE-C Activities

During the first part of the program the APE-B flight configuration was flown on several mission. As an additional task we prepared the APE-C Infra Red (IR) photometer for shuttle flights and completed flight qualification of this instrument. The instrument is shown on **Figure 6**. The APE-C hardware consisted of a IR photometer with a circularly variable filter with a thermoelectrically cooled PbS detector. In order to make useful measurements the instrument had to be interfaced mechanically with APE glow intensifier shuttle flight hardware. It was essential to record an image around the photometer field of view. Thus a suitable coupling was designed which permitted the mechanical mounting of the image intensifier on the IR photometer. The mechanical configuration of the two coupled instruments are shown on **Figure 7** In addition a suitable data recorder/flight computer had to be built. The whole system was built and flight qualified.

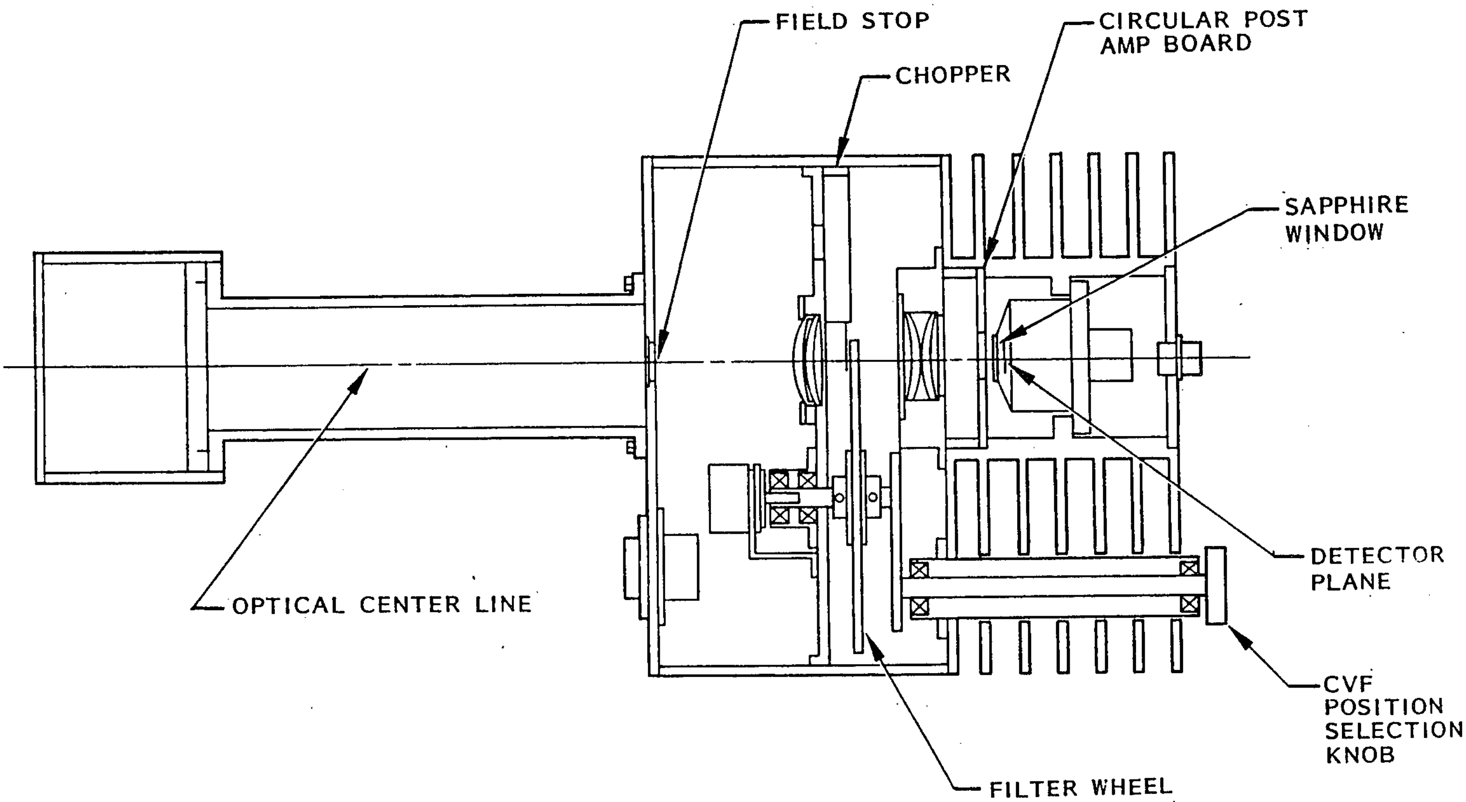

Figure 7. Drawing of the Coupled instrument.

3.2. Further APE B Flights

There were two flights scheduled for the APE-B equipment in calendar year 1993. The two APE flights STS-38 and 43 were extremely successful. Excellent data was taken on shuttle glow spectra, thruster induced glows and airglow. The APE-B flight hardware was also flown successfully on STS-51.

3.3. Data Analysis

We have analyzed the airglow data taken on the STS-38 and 43 missions and a paper [Mende et al., 1993] was published in the Journal of Geophysical Research. This paper described the observation of a high latitude NO_2 layer and showed the wavelength dependence of the airglow continuum.

The main thrust of the data in this paper was analyzing the airglow calibration data taken during the STS-38 APE experiments. This data are unique which permits obtaining the altitude distribution of the airglow emissions. The airglow spectrum taken on STS-38 is the best ever limb spectra of the night airglow taken from the shuttle orbiter. It reveals the altitude distribution of every known airglow line in the visible spectral region.

In the original version of the paper, we had provided measurement data in the form of limb intensity profiles as seen by the optical instrument flown on the shuttle. It was recommended to us by the referees that the data should be turned into volume emission rate profiles. This required the inversion of the limb intensities. For the inversion, we would have liked to use some existing codes such as the one used by our Canadians colleagues. We have acquired the code but found that when applied to our data the results were unsatisfactory. We devised our own method of forward modeling. According to this technique, we parameterized the volume altitude profile in terms of a "gaussian" altitude profile with two parameters: one describing the altitude of the gaussian peak and the other the altitude (thickness) of the layer. We selected appropriate parameters and integrated the volume emission rates along the line of sight to provide the calculated limb intensity distribution. This calculated distribution was compared to the data. The appropriate parameters were selected by comparing the calculated and observed profiles to obtain the best fit by eye.

This above procedure allowed us to obtain the absolute volume emission rate altitude dependence for the observed layers. The volume emission rates were obtained at various key wavelength regions. From these, we were able to obtain the wavelength dependence of the volume emission rates of the various airglow components. Probably the most significant result is the wavelength dependence of the airglow continuum. From these results, we can show that in the blue green region there is a continuum emission due to the NO_2 in the atmosphere. In our data, we did not see a previously reported strong red infrared component of the continuum.

To continue the improvement in the understanding of spacecraft glow phenomena we recommend that observations should be conducted. To pursue the IR observations most effectively, a near IR instrument should be developed. Such an instrument could be built and used first in ground based experiments for investigating thruster plumes with a telescope at a ground based facility (e.g. the Maui Air Force facility). At satisfactory conclusion of the ground based tests it would be recommended that the spectrometer should be modified to fly on the shuttle orbiter in the cargo bay on an Air Force supplied pointing mount. During the shuttle flight the intent would be to measure the spatial/spectral distribution of the IR glow emitted by the vehicle and its thruster plumes with this instrument.

For the IR observations in the 1 - 3.2 μm range, we suggest the development of a novel spectrograph using a focal plane array. It will be shown that this spectrograph is very sensitive and will provide the spatial/spectral profiles needed to interpret the data. The proposed spectrometer is shown in **Figure 8,** coupled to a "typical" telescope with a pair of doublets, for matching the telescope F/# 5 to the spectrometer F/# 2.5; a field lens is included to image the telescope exit pupil onto the following pupil. The spectrometer, with the second doublet, comprises a detachable assembly, which can be fitted to a given telescope with adjustments in the field lenses, or it can be operated independently. We propose this independent configuration for the experiments in which the instrument is flown on the shuttle.

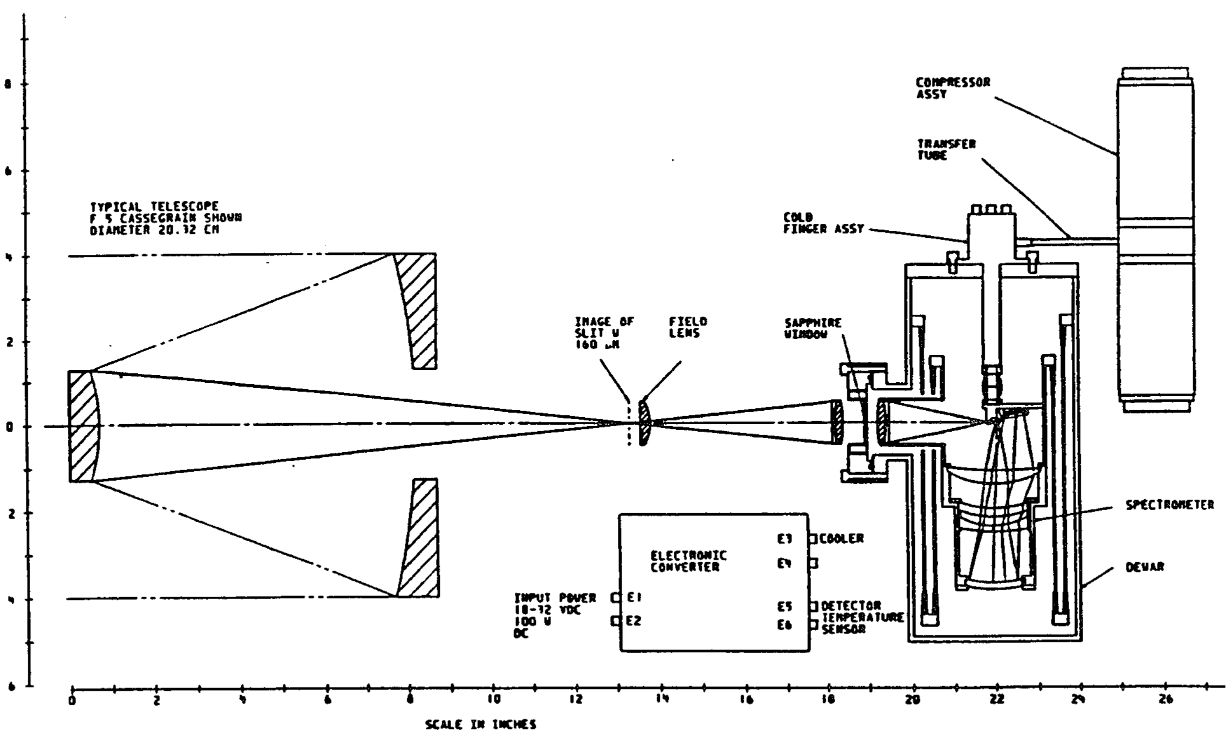

Figure 8. Illustration of the IR spectrograph

The preliminary design for this spectrometer was done for the Pluto Fast Flyby mission, where great emphasis was placed upon small size and low mass, as well as high performance. The small size of this spectrometer makes it quite easy to cool, and being cooled (nominally to the focal plane temperature), it provides a cold stop (exit pupil) to reduce background on the focal plane. The slit is also cold, which is important as it is imaged on the focal plane. For a preliminary baseline we have chosen the Magnavox MX7049 dual opposed piston split Stirling cooler. This cooler is readily available, will operate in space, and has low vibration. It is probably of greater cooling capacity than required to maintain the focal plane and spectrometer at 77K. As part of a detailed design effort the cooling requirement will be reviewed to optimize the choice of cooler.

The spectrometer (**Figure 9**) is an F/2.5 modified Rowland arrangement with a reflective, concave, linear grating. The first element beyond the slit is a field lens which images the exit pupil of the imaging optics onto the grating to minimize its size (nominally 31 mm in diameter). A small plano mirror, located near the field lens, folds the light path to improve access to the focal plane array. Between the focal plane and the grating are three correcting lenses that are used in double pass. These elements have little power but are used to cancel the aberrations of the concave spherical grating.

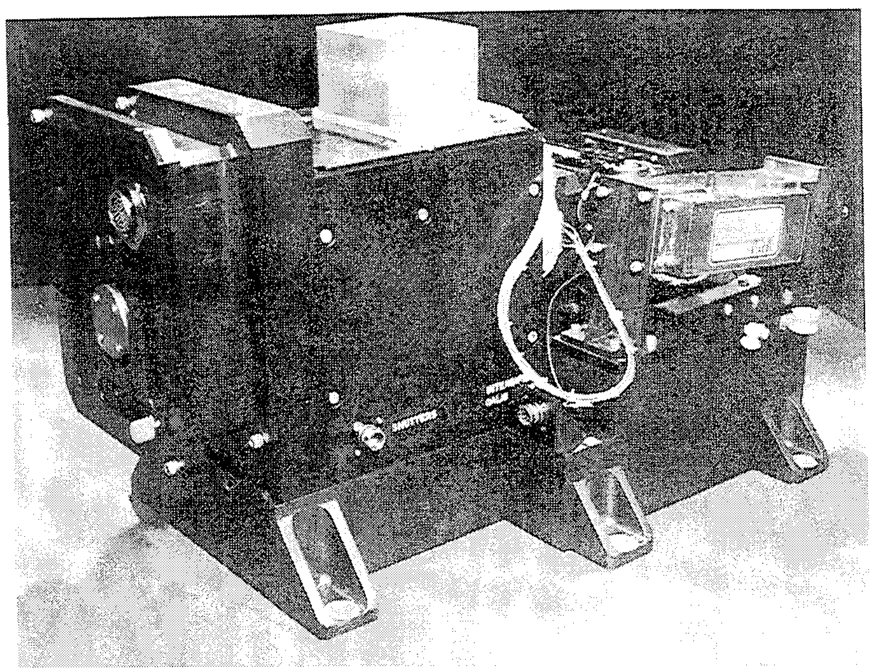

Figure 9. A view of the Lockheed FUV spectrometer from the Experimental Investigation of Shuttle Glow (EISG) experiment.

The spectrometer refractive elements are made of zinc selenide and cadmium telluride. The grating has a frequency of (nominally) 57 grooves/mm, which is appropriate to disperse the spectrum, from 1 µm to 3.2 µm, over the 1.024 cm focal plane. The grating will be slightly tilted (<2 degree incident angle) to reflect zero order energy to an absorber on the other side of the slit from the detector. Cold filters will be mounted on the focal plane or on the image side of the last field lens (as shown in **Figure 9**) for order sorting and background rejection. The filters would nominally cover the intervals 1 to 2 μm and 1.9 to 3.3 μm. The resolution established by the grating is given by

$$R = w \cdot (\sin a \pm \sin b)/\lambda \tag{3}$$

where w is the grating width, a and b are the incident and refracted angles, and λ is the wavelength. Values of a and b are provided by American Holographic. For nominal design values of a and b, R is greater than limits imposed by the image of the slit on the focal plane (2 pixels wide). That limit is ≈ 0.018 μm. We have considered two options for the grating(s); 1) a single grating for the spectral range from 1 to 3.2 μm, and 2) aperture sharing with split gratings. One of the "half" gratings would be designed for operation from 1 μm to 2 μm; the other "half" grating would operate from 1.9 μm to 3.2 μm. The values of a and b for the shared aperture gratings were also calculated by American Holographic. The single grating option is less expensive, simpler and provides effectively 1/2 the F/# achieved by the split grating option. With the single grating, the slit length covers the entire focal plane length so that 256 pixels could be summed for SNR enhancement (with the concomitant loss of spatial information in the direction along the slit length). In the split grating option, only 128 pixels can be summed along the slit length, for each of the half gratings. The single grating will, however, be less efficient than gratings optimized for approximately half of the spectral range. The grating efficiency values for the two options are given in **Table 1.0** (calculations from American Holographic). Our preliminary choice is the single grating approach for simplicity and lower cost. In the proposed effort, we would perform a more detailed system trade study which would include the relative importance of different wavelengths to make the optimum compromise. At that time, we would also consider such options as a flat grating. For the performance calculations summarized in this proposal, we have used the value of grating efficiency for the single grating option (21% at 3 μm).

Table 1. IR Table

GRATING EFFICIENCY (from American Holographic)

SINGLE GRATING BASELINE

wavelength, μm	efficiency, %
for 5000 Angstrom groove depth:	
1.0	8.0
1.7	34.0
2.0	33.0
3.0	20.7
3.2	18.8
for 6500 Angstrom groove depth:	
1.0	1.0
1.5	18.8
2.0	35.0
2.5	32.8
3.0	28.6
3.2	26.7

SHARED APERTURE OPTION

grating #1: 1.0 - 2.0 μm, 3800 Angstrom groove depth:	
1.0	27.3
1.5	32.3
1.9	26.2
grating #2: 1.9 - 3.2 μm, 7500 Angstrom groove depth:	
2.0	28.0
2.5	33.8
3.0	32.1
3.2	30.7

Two options have also been considered for the focal plane: 1) an existing HgCdTe array in the possession of the Air Force with detector composition optimized for response up to 5.5 μm wavelength, and 2) a version of the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) [Vural et al.,, 1990; Rieke et al., 1993 a, b] focal plane with response optimized for operation up to 3.2 μm (cutoff wavelength ≈ 3.55 μm). In Table 2, all relevant system parameters are given and the performance is compared for the two focal planes. The focal planes are both assumed to be at 77K. The spectrometer temperature could be allowed to rise to 190K without significant performance degradation.

The performance with different assumptions is summarized in **Table 2.0.** There we have attempted to compare the performance with that of the SKIRT spectrometer [Ahmadjian et al., 1992]; This is a difficult comparison as the operational wavelengths are different; our proposed instrument operates below 3.2 μm vs 5.4 μm for SKIRT, which gives us a lower NESR. Our spectral resolution is higher, which imposes an NESR penalty, and the integration time used in the SKIRT NESR calculation is not entirely clear from the reference [Ahmadjian et al., 1992]. The performance calculations for the grating instrument are done for the case of maximum spatial resolution along the slit, (each detector element is 40 μm x 40 μm; no pixel summing along the slit) so that our field of view is much smaller than that of the SKIRT instrument. The grating spectrometer provides inherently longer integration times than achievable with the circular variable filter in SKIRT, for the same spectral coverage. Operating at the shorter wavelength probably obviates the requirement for chopping (SKIRT uses synchronous detection). In Table 2.0 we have shown the performance for the grating spectrometer coupled to a warm telescope and operated with all cold optics. Also shown is performance with the resolution artificially broadened to that of the SKIRT spectrometer for purposes of comparison. The calculations show a significant performance advantage with the extended wavelength response (3.2 μm) NICMOS focal plane.

Table 2. IR Table

<u>Proposed Spectrometer:</u> resolution = .018 μm (17.58 cm^{-1}); integration time = 1 second; detector temperature = 78K.

detector peak wavelength, μm	5.5	5.5	3.2 (NICMOS)	3.2 (NICMOS)	
	with warm telescope	cold optics	with warm telescope	cold optics	
NESR @ 2.8 μm	7.03×10^{-8}	6.73×10^{-8}	2.04×10^{-8}	6.14×10^{-10}	$(W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1})$
NESR @ 2.8 μm	7.20×10^{-11}	6.89×10^{-11}	2.09×10^{-11}	6.29×10^{-13}	$(W \cdot cm^{-2} \cdot sr^{-1} \cdot cm^{-1})$

<u>Proposed Spectrometer:</u> resolution = 2% of 3.2μm, for comparison with SKIRT; integration time = 1 second.

detector peak wavelength, μm	5.5	5.5	3.2 (NICMOS)	3.2 (NICMOS)	
	with warm telescope	cold optics	with warm telescope	cold optics	
NESR @ 2.8 μm	1.98×10^{-8}	1.89×10^{-8}	5.75×10^{-9}	1.73×10^{-10}	$(W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1})$
NESR @ 2.8 μm	2.03×10^{-11}	1.94×10^{-11}	5.89×10^{-12}	1.77×10^{-13}	$(W \cdot cm^{-2} \cdot sr^{-1} \cdot cm^{-1})$

<u>SKIRT:</u> resolution = 2% of 5.4 μm; detector and optics temperature = 58K; Δf = 17 Hz.

NESR @ 5 μm		6.0×10^{-12}			$(W \cdot cm^{-2} \cdot sr^{-1} \cdot cm^{-1})$

4.0. Summary

In this program entitled Spacecraft Optical Environment the Lockheed Palo Alto Research Laboratory conducted a research program to investigate spacecraft interactions with the low earth orbit environment. This program was intended to investigate all aspects of spacecraft induced optical luminous phenomena and the backgrounds associated with the observation of such glows. The knowledge of the properties and the production mechanism of different types of spacecraft induced radiation has application in spacecraft borne remote sensing, the detection and identification of spacecraft, and in the diagnostics of the physical and chemical interaction between spacecraft materials and their environment. Great progress was made during the program in understanding thruster induced spacecraft glow in the visible and near IR spectral region. It was observed that during thruster firings some of the meta stable airglow components are excited such as the 557.7 and the 630 nm emission. The exact mechanism for this excitation is still somewhat controversial. Great progress was made in interpreting limb airglow profiles from orbit. Such investigations contribute to understanding the behavior of the upper atmosphere. As part of this report we discuss observations which are still needed to answer questions related to thruster firings and other time dependent glow phenomena. The methodology of observing emissions in the near IR requiring the construction of an IR (1 to 3.2 μ) imaging instrument was also discussed. A spectrograph that covers the wavelength simultaneously and which has one dimensional imaging capability was considered as an ideal instrument for this purpose. It is recommended that such an instrument should be field tested by observing the shuttle thruster plumes from the ground at the AMOS test facility through a telescope. It was further recommended that the instruments could be modified for shuttle flight and that the Air Force should perform a shuttle flight experiment with such an instrument. The above conclusions suggest a follow on program. An alternative more cost effective approach was also suggested in which only ground based measurements would be made with an existing Michelson interferomenter.

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